Enhanced architecture to suppress Rayleigh backscattering in colorless WDM-PON

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In this paper, an architecture of colorless wavelength-division-multiplexed passive-optical-network (WDM-PON) has been proposed to suppress Rayleigh-backscattering which is capable of supporting 10 Gbps data symmetrically both in downlink and uplink routes over 60 km standard single-mode fiber (SSMF). Simulation results show that the proposed architecture with Manchester coded downlink and Differential-phase-shift-keying (DPSK) modulated uplink supporting a data rate of symmetrical 10 Gbps over a transmission distance of 60 km can be implemented as the potential candidate for next-generation-PONs (NG-PONs). The proposed study is also extended and studied for orthogonal-frequency-division-multiplexing (OFDM) modulated downlink and DPSK modulated uplink.

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1. Introduction

The function of wavelength-division-multiplexing (WDM) techniques to the next generation optical access networks has become eye-catching for researchers due to various advantages such as high bit rate, reduced optical path-loss, point-to-point connectivity, bit-rate transparency, scalability, and flexibility. Numerous solutions have been recommended for WDM-passive optical networks (WDM-PONs), based on different colorless optical network units (ONUs). Several key enabling technologies have been reported for converged WDM-PON systems, including the practices for longer reach, high security, higher data rate, and higher spectral efficiency [1]. In the implementation of the low-cost WDM-PON, the colorless ONU is a vital and key component. One promising solution for broadband colorless ONU is the optical loopback method, but in this loopback network intrinsic Rayleigh backscattering (RBS) induces crosstalk to uplink signal and cause degradation of bit error rate (BER) at the receiver of the optical line terminal (OLT). Rayleigh backscattering (RB) is the main transmission impairment which affects the performance of colorless WDM-PON. High pass filtering (HPF) shows the potential technique to get rid of RB noise was described in the central light source passive optical networks (CLS-PONs) because it improves the system performance without any additional hardware [2]. The proper filter cutoff frequency depends on signal extinction ratio (ER) and pattern length. Appropriate HPF diminished RB noise sensitivity in low ER signals by more than 10 dB. This can potentially trim down the cost of future CLS-PONs. Carrier distributed architecture is susceptible to interferometric crosstalk induced by RB, and magnitude of this noise greatly enhanced due to incoherent detection of Rayleigh light because of the coherent nature of the detection [3], [4].

Several methods to reduce interferometric noise are suggested which included use of Reflective Semiconductor Optical Amplifier (RSOA) based transceiver in the ONU and phase scrambling to diminish crosstalk in the implementation of the WDM system. However, these schemes were susceptible to dispersion [6-8]. The beating noise was primarily allocated in the lower frequency region after detection. Electrical HPF may be used to suppress this crosstalk [9], [10]. These architectures need only slight variations in the PON configuration. However, electrical equalization or suitable line coding was necessitated to remove the HPF-stimulated distortion in the transmission of the uplink signal. Additionally, the accounted enhancement in RB noise tolerance was also bound to 5 dB. At the digital decision of the OLT receiver, Quantized-feedback equalization can be employed that permits recovery of the low-frequency components subsequent to filtering out the associated distorting RBS noise added in the transmission of the bidirectional WDM-PON, obtained a substantial increase in the tolerance [11].

A novel scheme to suppress RB noise in carrier-distributed WDM-PON has been reported [12, 13] by using differential phase- shift keying (DPSK) as the modulation format for uplink transmission and narrow spectrum noise was well suppressed by the notch-filter similar to delay-interferometer (DI) at the OLT. This achieved with less than 0.2 dB power penalty stimulated by RB noise over 20 km transmission, but requiring extra external modulators at ONU and complex de/modulation circuits [12], [13].

The crosstalk had been induced by both carrier RB and signal RB during uplink transmission [14-17]. By increasing the gain of ONU there is an increase in signal to carrier RB and by decreasing the ONU gain signal to signal RB ratio decreases so there is a need to take the optimal value of ONU gain. Carrier RB is principal RB noise within transmission over 60 km [18] hence efficient suppression of the carrier RB is vital in the implementation of RB noise resistant uplink receivers in WDM-PON. The DI performs two operations that are Optical equalization and vestigial optical filtering, from which enhancements in bandwidth and receiver sensitivity can be achieved [19-21].

In this paper, an architecture of colorless WDM-PON operating symmetrically 10Gbps to suppress the RB noise has been proposed using different line coding for downlink and DPSK for uplink transmission respectively. Destructive port of DI is used at OLT to suppress the carrier RB and simultaneously acts as a DPSK demodulator. DPSK is used here for uplink transmission due to its lower power penalty for uplink transmission. Then we have used different line coding for downlink transmission and analyze the results. Simulation is performed using OptiSystem [22] for the proposed architecture with 16 downlink and 16 uplink unicast channels operating symmetrically 10 Gbps having acceptable performance.

A re-modulation scheme had been proposed earlier in [23] with finite extinction ratio (ER) for colorless WDM-PON using downlink OOK and uplink DPSK symmetrically at the data rate of 10 Gbps. This scheme is capable of transmission over 30 km distance in the downlink by employing OOK having receiver sensitivity of around -15.8 dBm at BER=10^{-9} without dispersion compensation. In comparison to [23], the proposed scheme is capable of transmission up to 60 km in downlink without dispersion compensation with better receiver sensitivity (BER=10-9) at the data rate of 10 Gbps by employing Manchester coding for downlink and illustrated in results and discussions. Further, here we have also analyzed carrier RB, signal RB and their mitigation using DI. Various literatures have been presented earlier [24-26] using different modulation formats to achieve WDM-PON.

The remaining paper is organized under following headings- Proposed Architecture to suppress the RB noise, Results, and Discussion to describe the various results and in the last Conclusion.

2. Proposed architecture

Fig. 1 demonstrates the proposed architecture to suppress the RB noise. In the downlink transmission, 16 downlink unicast channels (192.8 THz to 194.3 THz with 100 GHz channel spacing) are used. Simulation is performed using commercially available OptiSystem [22] software. All the downlink data are modulated on a different wavelength with the help of $LiNbO_3$ Mach-Zehnder modulator (MZM) using line coding and multiplexed by array waveguide grating (AWG) (insertion loss = 4 dB, channel spacing = 0.8 nm and 3-dB bandwidth = 0.6 nm) at OLT. Then the output of the AWG is fed to 50 km bidirectional fiber (Dispersion = 16 ps/(nm-km), dispersion slope = 0.075 ps/(nm^2-km), attenuation = 0.2 dB/km) with the help of an optical circulator. The output of bidirectional fiber is then again fed to an AWG present at the remote node (RN) to de-multiplex the downlink signals. The different demultiplexed downlink signals are then fed to different ONUs using 10 km distribution fiber.

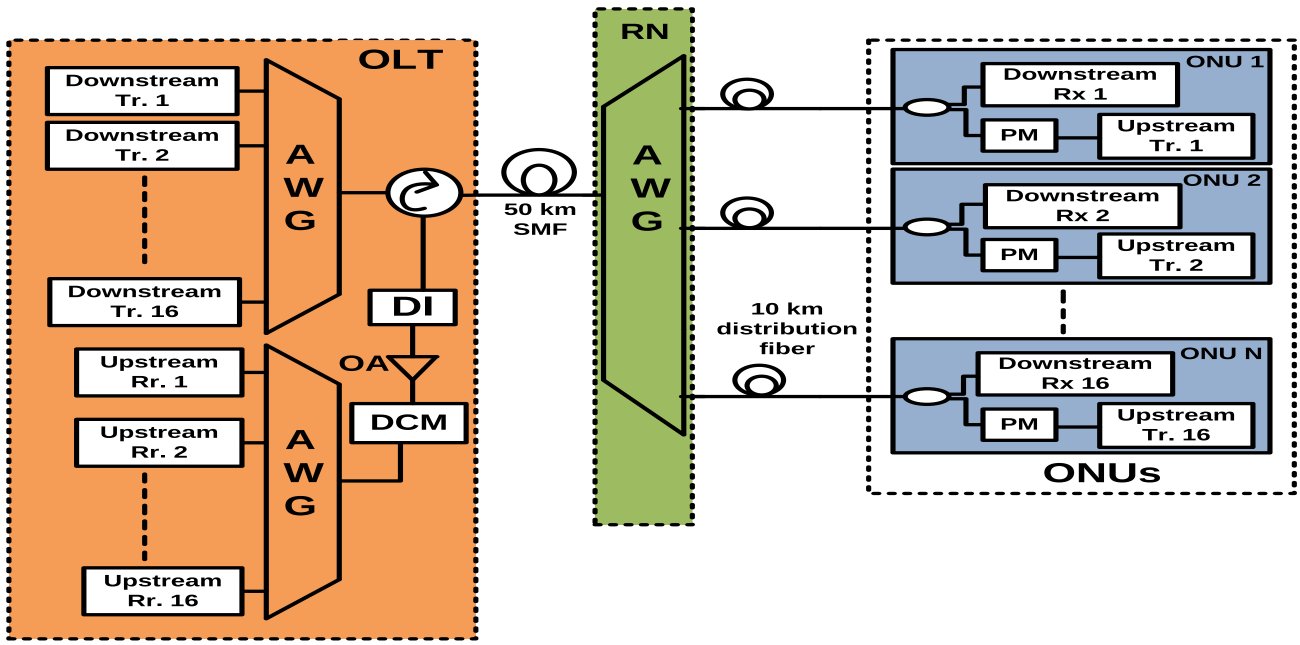

Fig. 1. Schematic of the proposed colorless WDM-PON

At each ONU the received downlink signal is first fed to a 50:50 bidirectional coupler one is used for downlink detection and another is used for uplink modulation. At each ONU, the CW light is amplified before modulation by an optical phase modulator (PM), and then loop-back to the OLT. Since the optical signal received from central office has been reused for upstream transmission therefore no extra laser source need to be employed at ONUs. This technique is called 'colorless' operation of ONUs. The optical PM has been driven by a differential pre-coded uplink signal. For uplink modulation, DPSK modulation has been selected since it has a high tolerance for RB. All the uplink DPSK signals then multiplexed by the same AWG at RN traveling through same 10 km distribution fiber. The output of the AWG is fed to OLT using a coupler and same 50 km SMF. The received uplink DPSK signals at OLT are first fed to a DI that will work as a notch filter and DPSK demodulator. For the suppression of RB, it is essential to use DI's destructive port. Due to the DI's periodic frequency response, One DI (relative delay = 94 ps) at OLT is sufficient to demodulate all multiplexed uplink DPSK signals. The output of the DI is amplified by an optical amplifier at OLT and then fed to a dispersion compensated module (dispersion = -960 ps/nm-km) to compensate the accumulated dispersion of 60 km fiber. The output of DCM is demultiplexed by AWG and simultaneously received at OLT.

3. Results and discussion

First, we have analyzed the carrier backscattering and then signal backscattering for DPSK signal. Fig. 2 shows the architecture that is for the calculation of carrier RB. In this architecture, a CW laser having wavelength of 1553.5 nm is first fed to a 20:80 coupler so that the total power of CW laser is divided into 20 and 80 ratios. The upper 20% of CW laser power is fed into the 50 km SMF using a circulator. Rayleigh backscattering of bidirectional SMF is set to (5×10^{-5})/km. The other 80% of the CW laser power is fed to a PM and modulated by 10 Gbps (2^{31}-1) PRBS data to generate DPSK data. The Rayleigh backscattered signal from 50 km bidirectional optical fiber and modulated 10 Gbps DPSK data are sent to power combiner. The combined output of power combiner is fed to a DI. The destructive port of DI is working as a notch filter and reduces the RB noise. The output of the DI is amplified by an EDFA and received by a 10 Gbps PIN receiver.

The effectiveness of the DI's destructive port has been investigated in Fig. 3 on the suppression of the RBS based on the schematic depicted in Fig. 2. The correlation between the average reflected power and the average input CW light power has been measured for the transmission over 60 km SMF. Two cases have been considered and studied to suppress the RBS that are with and without employing the destructive port of the DI. For any given system, the corresponding RB noise has been reduced by more than 10 dB by employing DI.

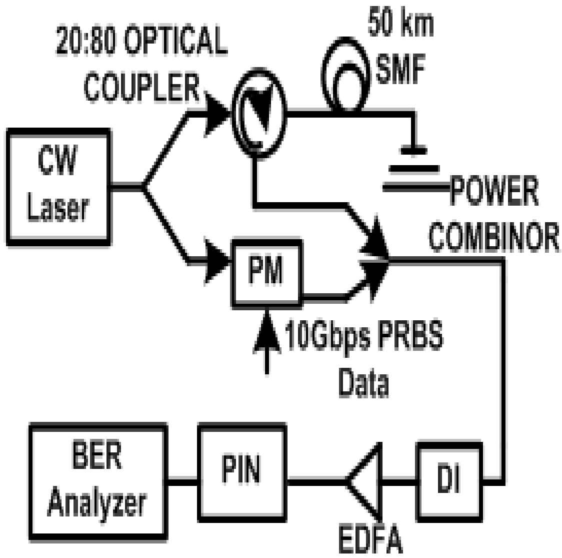

Fig. 2. System modeling for calculation of carrier RB

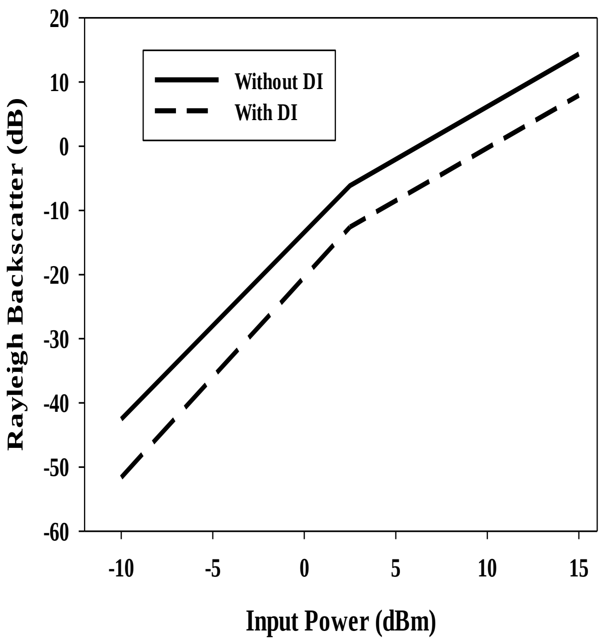

Fig. 3. Plot for Rayleigh backscatter at different input power

The narrow spectrum carrier RB at 1553.5 nm wavelength is efficiently eliminated by the destructive port of the DI. The destructive port of the DI is also working as a DPSK demodulator, and depicted in Fig. 4(a) and Fig. 4(b). The blue line shows the Rayleigh backscatter noise.

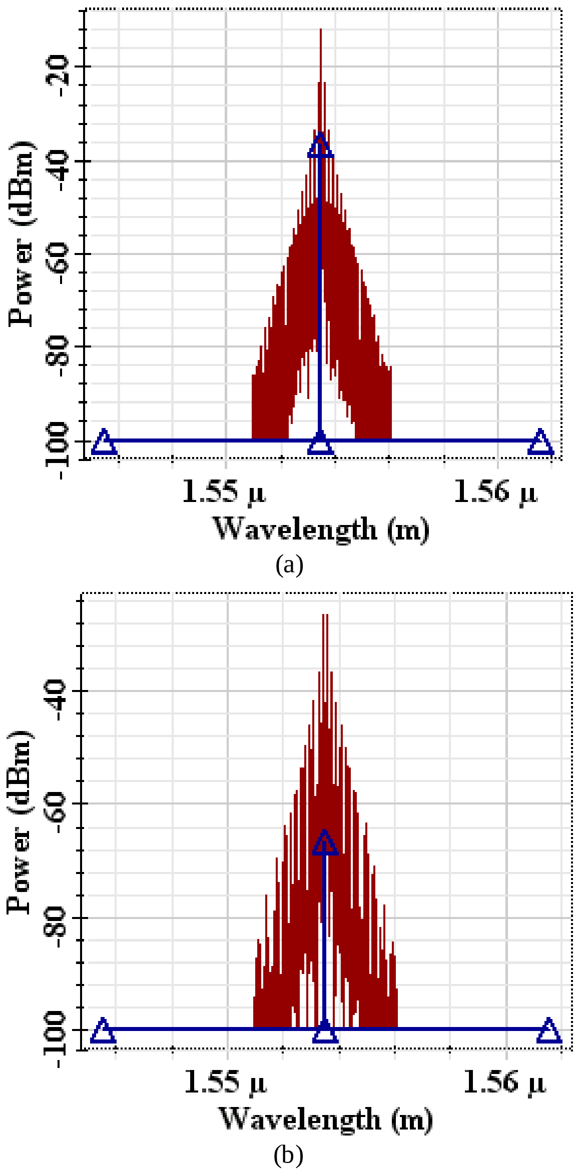

Fig. 4. Optical spectrum of downlink signal (a) before DI (b) after DI

Fig. 5 shows the architecture that is for the calculation of signal RB. In this architecture a CW laser having wavelength 1553.5 nm of is first fed to a 20:80 coupler so that the total power of CW laser is divided into 20 and 80 ratios. The lower 80% of CW laser power is fed PM and modulated by 10 Gbps (2^{31}-1) PRBS data to generate DPSK data. This modulated data is then sent to the 50 km SMF using a circulator. Rayleigh backscattering of bidirectional SMF is set to (5×10^{-5}) /km. The Rayleigh backscattered signal from 50 km bidirectional optical fiber and 20% of CW LASER power are sent to power combiner. The combined output of power combiner is fed to a PM again to modulate 10 Gbps PRBS data to generate DPSK data. Then the output of the second PM is fed to DI. The destructive port of DI is working as a notch filter to mitigate the RB noise. The output of the DI is amplified by an EDFA and received by a 10 Gbps PIN receiver.

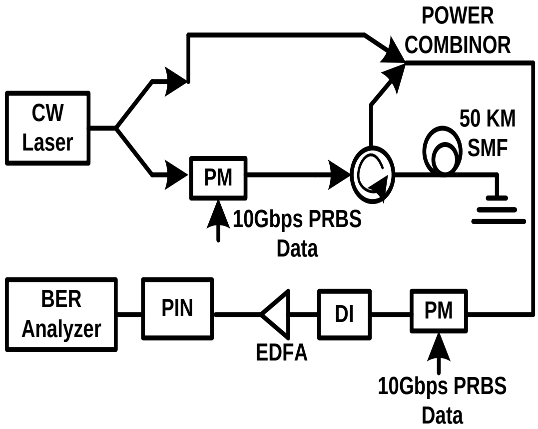

Fig. 5. System modeling for calculation of carrier RB

Fig. 6 shows the signal RB before and after DI. The blue line shows the Rayleigh backscatter noise. Fig. 6 (a) shows the waveform before the DI and Fig. 6 (b) shows the waveform after the DI. From these two waveforms, we conclude that the signal RB before DI is about -70 dB and after the DI it is approximately -40 dB so signal RB not very much reduced by this technique.

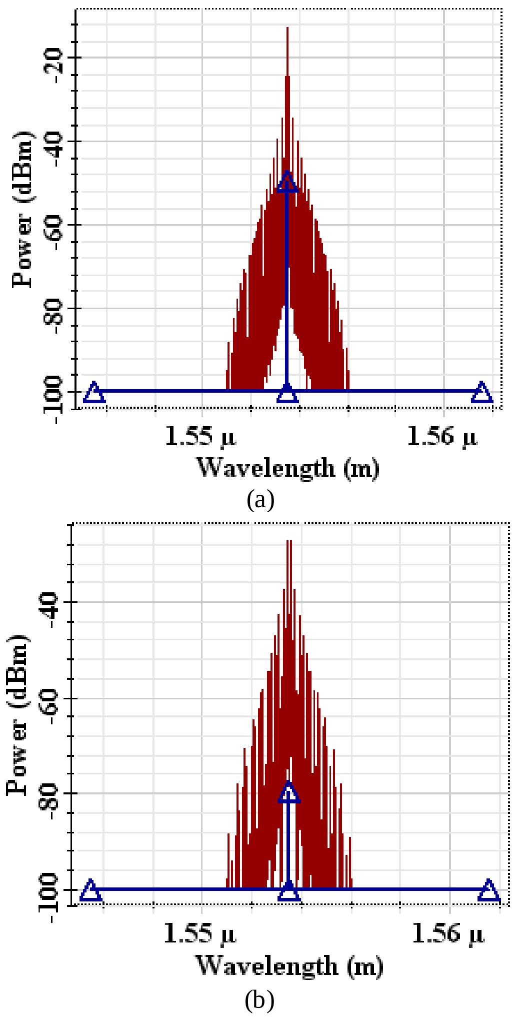

Fig. 6. Analyzation of signal RB (a) Before DI (b) After DI

As shown in Fig. 7 we have compared two basic modulation schemes OOK modulation and DPSK modulation. In our scheme, DPSK modulation has been adopted which gives power penalty less than 1 dB in both proposed work and our simulated model in Fig. 2. And for OOK modulation power induced reaches to 7 dB at a low power level in the proposed work and the simulated model penalty is nearly 6 dB. The uplink power penalty has been investigated as a function of the signal-to-crosstalk ratio (SCR) of the scheme shown in Fig. 2.

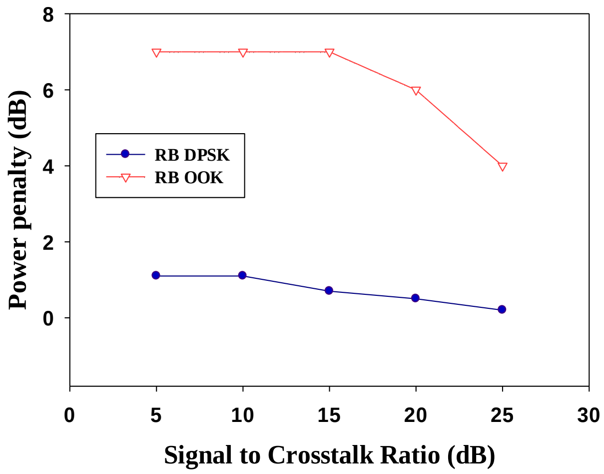

Fig. 7. Plot for Power Penalty (at BER=10^{-9}) for different Signal to Crosstalk Ratio

Fig. 8 represents the result of simulation model given in Fig. 2. From this, we can see that in the case of received power lower than -35 dBm, log(BER) is lower than -4 for proposed simulated model and for received power well above than sensitivity (> -28 dBm) of receiver both the model show log(BER) well above -9 with approximate same value.

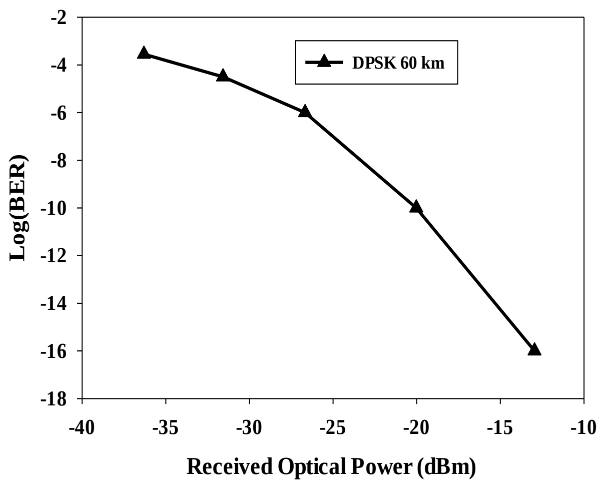

Fig. 8. Plot for Log(BER) at different Received optical Power

In the proposed work we have ignored other sources of crosstalk i.e.; Raman scattering, Brillouin scattering, Four Wave Mixing etc. We have mainly concentrated on the crosstalk induced by Rayleigh noise in the simulation model and worked for reduction of Rayleigh noise which also improves the system performance of WDM-PON.

For further improving system tolerance against RB noise we have used different line coding schemes, i.e.; RZ, NRZ, and Manchester for downlink signal. As shown in Fig. 9, Rayleigh backscatter for NRZ and RZ modulated signal is reduced as compared to the un-modulated signal. As compared to un-modulated signal Rayleigh noise is reduced by 2 dB and 2.4 dB respectively for NRZ and RZ coded signal. Thus improved BER can be assured for line coded downlink signal.

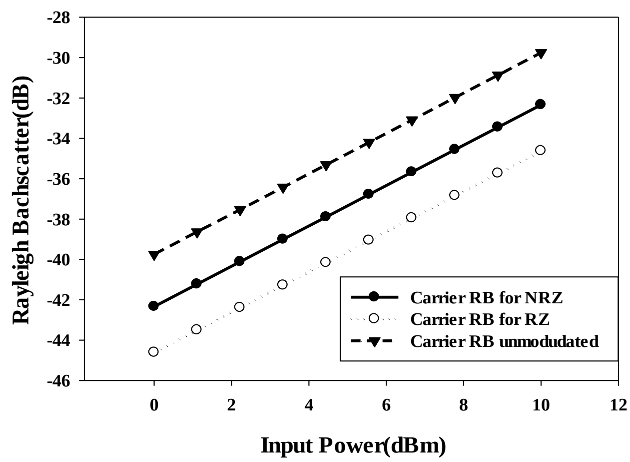

Fig. 9. Input power vs. Rayleigh Noise using Different Line Coding Schemes

Fig. 10 shows the minimum Log(BER) versus input power (dBm) while varying the modulation formats of downlink signals (NRZ, RZ, and Manchester line coding). The figure shows log(BER) = -3 for NRZ and -6 for RZ coded signal and for Manchester coding Log(BER) is substantially improved to -19. Thus, it can be summarized that compared with the NRZ and RZ code, the power budget of WDM-PON can be substantially improved with Manchester code.

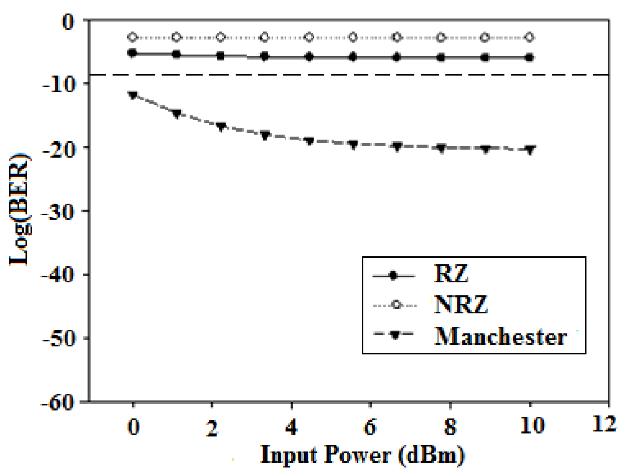

Fig. 10. Input Power vs. Log(BER) for Loopback Architecture

Table 1 compares the performance of different coding techniques and un-modulated downlink transmission using the simulation setup given in Fig. 1 for various parameters such as min. BER, Max. Q-factor and threshold. It is evident from Table 1 that Manchester coding technique yields better min. BER and Q factor in comparison with RZ and NRZ. Hence, from our study, we propose Manchester coding to be employed for WDM-PON transmission. Fig. 11(a), 11(b) and 11(c) show the eye diagrams for the transmission of NRZ, RZ and Manchester coded data respectively.

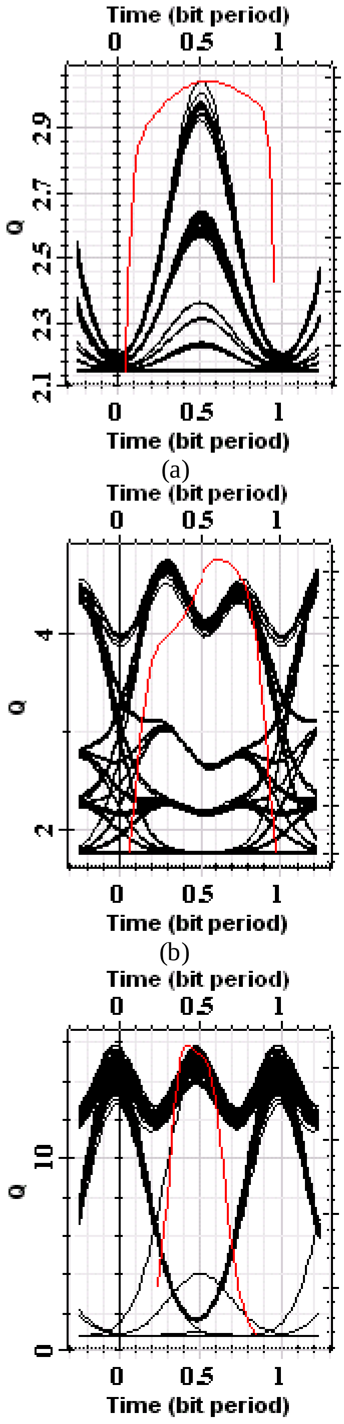

Fig. 11. Eye diagrams for the transmission of (a) NRZ (BER=10^{-4}) (b) RZ (BER=10^{-7}) (c) Manchester coded data (BER=10^{-19})

Table 1. Specification of different simulation parameters

Analysis	Min. BER	Max. Q Factor
NRZ	11.71×10^{-4}	3.04
RZ	8.87×10^{-7}	4.77
Manchester	5.48×10-19	12.8
Un-modulated	5.34×10-25	15.81

Based on the model described in Fig. 1, the bit error rate (BER) has been measured for downlink signal modulated in Manchester line coding and DPSK modulated uplink transmission over 60 km SMF and back to back (B2B) transmission for different received optical power and shown in Fig. 12. The input power at SMF for each channel is taken as 10 dBm in the Manchester coded downlink transmission because beyond 10 dBm input power, the non-linearity in the fiber become dominating. For upstream transmission, the power at the output of each PM is set as 8 dBm. The worst receiver sensitivity has been calculated as the received optical power corresponding to BER = 10^{-9}. For downlink Manchester transmission, the worst receiver sensitivity of -18.98 and -18.9 dBm has been obtained over 60 km SMF and B2B transmission corresponding to BER = 10^{-9}. For uplink DPSK transmission, the worst receiver sensitivity of -25.09 and -25 dBm has been obtained over 60 km SMF and B2B transmission corresponding to BER = 10^{-9}.

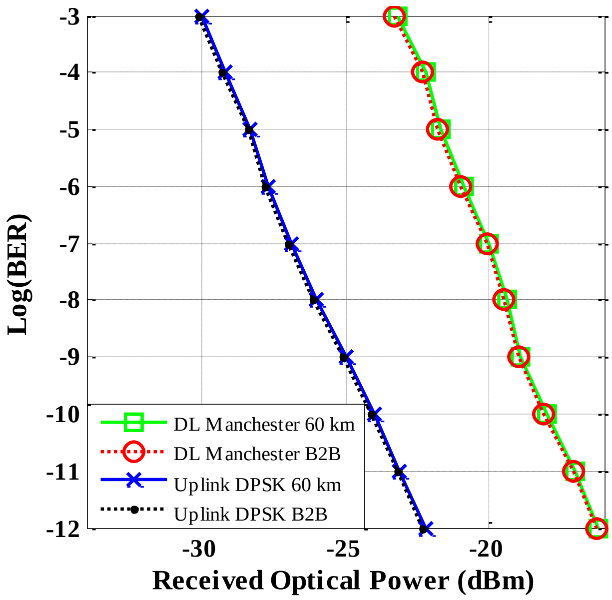

Fig. 12. Plot for Log(BER) at different received optical power for Loopback Architecture (DL: Downlink, UL: Uplink)

Finally, based on the model described in Fig. 1, the bit error rate (BER) has been also measured for downlink modulated orthogonal frequency division multiplexing (OFDM) direct detection (DD) signal and DPSK modulated uplink transmission over 60 km SMF and back to back (B2B) transmission for different received optical power and shown in Fig. 13. OFDM has been widely used in downlink PON transmission to increase the distance and supportable data rate of downstream signals [20, 21, 27, 28]. The parameters used for OFDM transmission and reception are same as that are used in [20, 21]. The major parameters are as follows: Subcarriers-512, Inverse fast Fourier transform/ fast Fourier transform (IFFT/FFT) points- 1024, Length of cyclic prefix (CP)- Symbol extension (25%), Prefix points- 0 and Quadrature amplitude modulation (QAM) levels- 4. The input power at SMF for each channel is taken as 10 dBm in the OFDM modulated downlink transmission. For upstream transmission, the power at the output of each PM is set as 8 dBm. The worst receiver sensitivity has been calculated as the received optical power corresponding to BER = 10^{-9}. For downlink OFDM transmission, the worst receiver sensitivity of -22.99 and -22.9 dBm has been obtained over 60 km SMF and B2B transmission corresponding to BER = 10^{-9}. For uplink DPSK transmission, the worst receiver sensitivity of –26.14 and -26 dBm has been obtained over 60 km SMF and B2B transmission corresponding to BER = 10^{-9}.

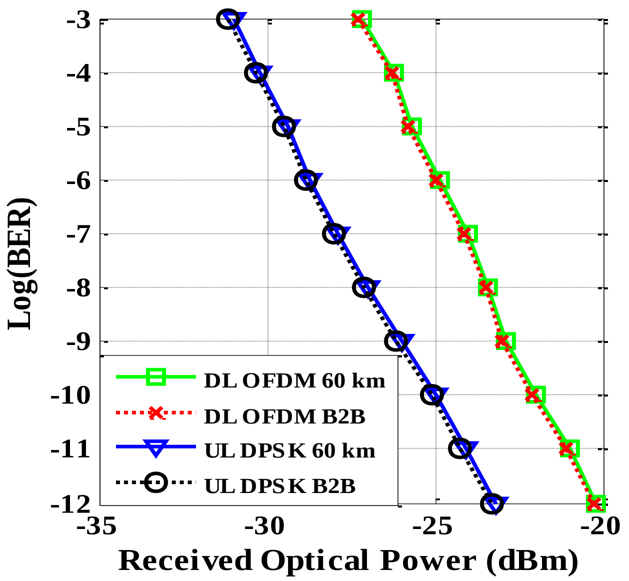

Fig. 13. Plot for Log(BER) at different received optical power for OFDM DL and DPSK UL Loopback Architecture (DL: Downlink, UL: Uplink)

4. Conclusions

In this paper, first the carrier RB and the signal RB have been calculated for the proposed architecture of colorless WDM-PON. In the study of the proposed architecture, we have used three key points for mitigating RB noise. First one is the use of DI, which reduces RB noise significantly by more than 10 dBm. Second is the use of DPSK modulation for uplink signal. From results, it is shown that using proposed scheme the power penalty for DPSK modulation is up to 1 dB only, whereas in the case of OOK modulation it reaches up to 6.5 dB, thus improved BER performance can be achieved using DPSK modulation. The third is the use of Manchester line coding scheme. In the study of proposed architecture, we get log(BER) = -3 for NRZ and -6 for RZ coded signal and for Manchester coding Min. log(BER) is substantially improved to -19 so concluded that Manchester coding is best one to use in the proposed architecture. Finally, the proposed symmetrical 10 Gbps transmission capable colorless WDM-PON architecture with Manchester or OFDM coded downlink and DPSK modulated uplink shows the acceptable performance as evident from above results and may be implemented in the next generation (NG)-PONs.

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